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A Study of the Charmonium Spectrum through Proton-Antiproton Annihilation: Results and Prospects at Fermilab

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I give a summary of the technique and results from Fermilab Experiment E760 which studied the Charmonium spectrum by resonant formation in Proton-Antiproton Annihilation; final results on measurements of the η_c and the search for the η_c' are given. Prospects for the continued study in a new experiment, E835, are also briefly presented.

1 Introduction

Fermilab experiment E760 was devoted to a study of the charmonium spectrum using the technique of resonant formation in $\bar{p}p$ annihilations. In a conference largely devoted to the complexities of light-quark spectroscopy it might be mentioned that the study of the charmonium spectrum in particular is immediately satisfying both to the experimenter because the first-order description for the masses and widths of the known states works so well and to the theorist because it provides a practical place to test techniques of QCD calculations beyond the lowest order. It is also useful to note that despite the impressive work at e^+e^- machines,[1] many important quantities of the Charmonium system remained to be measured after that work stopped.

As examples, the widths of the $^3P_{1,2}$ states were essentially unknown; the $^1P_1$ state was not observed; the width of the 1^1S_0 state, the η_c, was poorly known, and the observation of the excited state, the 2^1S_0 or η_c', reported at an unexpectedly low mass, remained to be confirmed (or corrected). [a] Proposed in 1985, E760 [2] took its first data in 1990.

Studying the resonant formation of charmonium in $\bar{p}p$ annihilations has some specific advantages. From the physics point of view, $\bar{p}p$ annihilations allow the charmonium states to be formed either by two or three gluons. Unlike the case at electron-positron colliding machines where only states with $J^{PC} = 1^{--}$ are produced directly, $\bar{p}p$ annihilations can produce all J^{PC} states accessible to $q\bar{q}$ directly. A technical advantage is that the accuracy and resolution in the mass and width measurements of the charmonium states are set by the parameters of the continuously circulating $\bar{p}$ beam and not by the final state detector, provided one has sufficient data.

[a] The convention for describing the states is N $^{2S+1}$L$_J$ where J = L + S; C = -1^{L+S} and P = -1^{L+1}.

There are, of course, some technical challenges to meet. The major one is provision of the antiproton beam; this is available courtesy the antiproton source for the high energy collider at Fermilab plus a significant amount of accelerator work to allow the antiproton beam accumulated to be *decelerated* from the accumulation energy of 9 GeV to the energy for charmonium formation of $\approx$ 5 GeV.[3] For the experimenter, the challenge is to construct a target to generate adequate luminosity, and an apparatus to identify and record the small cross-sections (nanobarns to picobarns) in a total cross section of 60 millibarns. The proof of principle was demonstrated by experiment R-704 at CERN.[4]

2 Experiment Technique

The experiment is located directly in the accumulator of the antiproton source at Fermilab and uses an arrangement in which a jet of hydrogen gas crosses the antiproton beam circulating in the antiproton accumulator. The average center of mass energy of the $\bar{p}p$ interactions is known to about 50 keV as evidenced by repeated scans at the J/ψ and ψ' resonances and the center of mass energy spread can be made as small as 250 keV. Charmonium states are detected through their electromagnetic decay modes e.g. $J/\psi \rightarrow e^+e^-, \chi \rightarrow J/\psi + \gamma, (J/\psi \rightarrow e^+e^-)$ and $\eta_c \rightarrow \gamma\gamma$ and the apparatus is optimized for the detection and identification of photons and electrons. Since the experiment requires a different beam energy than is used for collider operation, the experiment runs only during operation of the fixed-target program.

The detector [5] consists of a set of tracking chambers, scintillation hodoscopes for triggering and dE/dx measurement, a multi-cell Cerenkov counter for electron identification, a forward calorimeter and a central calorimeter of 1280 lead-glass Cerenkov counters arranged in a pointing geometry. It covers the full azimuth and the laboratory polar angle from 2° to 70°; the fiducial acceptance in the center of mass is approximately $-0.5 < \cos(\theta^*) < 0.5$.

The excitation curves are obtained by decelerating the antiproton beam from the accumulation energy to an energy just above the resonance and then decelerating through the resonance in steps of between 170 and 500 keV (center of mass energy) depending on the resonance. In our case the beam energy spread is small enough to allow the total width of the charmonium state to be determined directly from the shape of the excitation curve.[6] This is in contrast with the case of electron-positron annihilation where the total width is determined from the area under the excitation curve and the hadronic and leptonic branching ratios, a procedure which couples the determination of the widths to the measurement of the branching ratios.[7]

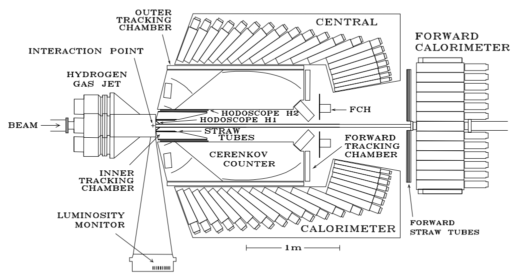

Figure 1: The E760 Detector

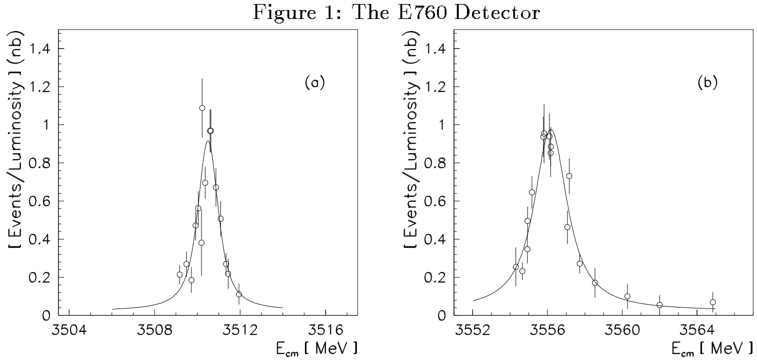

Figure 2: χ_1 (a) and χ_2 (b) excitation curves

3 Decays with a J/ψ in the Final State

As examples of our data, Figure 2 shows excitation curves measured for the χ_1 and χ_2 states; the beam energy spread is small compared to the widths of the states themselves. Table 1 shows the masses and widths of states as determined by E760 compared with previous measurements.

The values of the χ_1 and χ_2 total widths, and their ratio, can be compared to predictions assuming that the only significant decay modes are the radiative decays and the hadronic decays, $\chi_1 \to (q\bar{q}g)$ and $\chi_2 \to (gg)$. The radiative decay widths, which can be inferred from the radiative branching ratio and the total width, can also be compared with the simple electric dipole predictions.

The agreements are all quite satisfactory.[5]

The difference between the J-weighted average mass of the ^3P states and the $^1P_1$ mass is a measure of the Hyperfine (spin-spin) interaction in the L=1 state. For a short-range interaction, this difference is expected to be small, typically a few MeV. Thus the interpretation of any measurement of the $^1P_1$ mass depends on good precision in the masses of the χ states, particularly the χ_1 and χ_2. Details of the $^1P_1$ search and discovery are given in reference 8. The experiment observed a peak equivalent to a 3.6 sigma excess in the rate of $J/\psi\ \pi^0$ production at a mass of 3526.2±0.3 MeV/c^2 which we interpret as the $^1P_1$ state. No similar excess was found in the rate of $J/\psi\gamma$ production, a decay which is forbidden by C conservation. That we saw no excess in the rate of $\eta_c\gamma$, expected to be the major radiative decay, is consistent with reasonable expectations of the decay rates. The measured mass is about 0.9 MeV/c^2 above the center of gravity of the χ states, consistent with the calculation of reference 9.

4 Two Photon Final States

While the previous data all included a J/ψ in the final state, the experiment also has the ability to study $\gamma\gamma$ final states, which can arise from the continuum reaction $p\bar{p} \rightarrow \gamma\gamma$ and from decays of $C = +1$ charmonium states such as the $^1S_0$. The major background in the identification of $\gamma\gamma$ events comes from $\pi^0\gamma$ and $\pi^0\pi^0$ final states where photon(s) either fall outside the geomtric acceptance or are too low in energy ($<$ 20 MeV) to be detected. We have measured[10] the branching ratio $B(\chi_2 \rightarrow \gamma\gamma)$ to be $(1.6 \pm 0.5) \times 10^{-4}$ or equivalently a partial width $\Gamma_{\gamma\gamma} = 320 \pm 100$ eV. The branching ratio, $B_{\gamma\gamma}$, is the ratio of the electromagnetic and hadronic widths which to some order is given by $\frac{\alpha^2}{\alpha_s^2} \times \frac{(1-16\alpha_s/3\pi)}{(1-2.2\alpha_s/2.2\pi)}$. Within the theoretical uncertainty one can then extract a value of $\alpha_s \approx 0.35$.

The analysis of our measurement of the η_c and search for the η_c' in its two photon decay mode is about to be published.[11] Time limitations affected the precision of the measurement but even here the power of the direct production technique can be seen. Figure 3 shows the $\gamma\gamma$ yield from the η_c scan. There is a clear peak above a background from $\pi^0\pi^0$ and $\pi^0\gamma$ events with missing photon(s). Since the background is strongly peaked at large values of $\cos(\theta^*)$ and the η_c decay is isotropic, the acceptance is restricted to $\cos(\theta^*) < 0.25$. Though the statistics are poor, an immediate result is that the mass we observe is 2988±3 MeV/c^2, compared to the previous world average of 2980±2; for the η_c width we obtain $\Gamma_{total} = 24^{+12.6}_{-7.1}$ MeV. Using the published value for the branching ratio, $B_{\bar{p}p}$, we obtain $\Gamma_{\gamma\gamma} = (6.7^{+2.4}_{-1.7} \pm 2.3)$ keV which compares

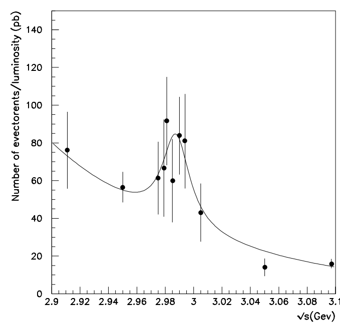

Figure 3: Mass Spectrum of Two Photon Event Candidates

reasonably with the result from CLEO.[12] The value of α_s derived from $B_{\gamma\gamma}$, given by $\frac{8}{9} \times \frac{\alpha^2}{\alpha_s^2} \times \frac{(1-3.4\alpha_s/\pi)}{(1+4.8\alpha_s/\pi)}$, is 0.29 ± 0.05.

We have made an extensive study of the background from $\pi^0\pi^0$ and $\pi^0\gamma$ events. The $\pi^0\gamma$ rate is inferred by taking the rate of fully reconstructed $\pi^0\pi^0$ events, calculating the number of events from this channel where one photon would be undetected and would thus appear as $\pi^0\gamma$, comparing this with the number of such events observed and attributing the difference to the process $\bar{p}p \rightarrow \pi^0\gamma$. Having subtracted the backgrounds due to $\pi^0\pi^0$ and $\pi^0\gamma$ from the $\gamma\gamma$ signal, we also set an upper limit on the real continuum process $p\bar{p} \rightarrow \gamma\gamma$ of less than 40 pb at $\sqrt{s} = 3$ GeV with $\cos(\theta^*) < 0.4$.

The time available for our search for the η_c' was limited and the result can be summarized by saying that we can neither exclude nor confirm the mass reported by the Crystal Barrel. Figure 4 shows a 95% exclusion plot for the process $\bar{p}p \rightarrow \eta_c' \rightarrow \gamma\gamma$ over the mass range 3.585 GeV/c^2 to 3.625 GeV/c^2. As can be inferred from the plot, we took data near the value reported by Crystal Barrel (3.59 GeV/c^2) and just below the value preferred by theory ($\approx$ 3.62 GeV/c^2). The figure shows two exclusion curves corresponding to different widths of the η_c'.

Naturally, this was not a very satisfying situation and so we turn to...

5 The future

For the future, a continuation proposal has been approved as E835 for the next fixed-target run at Fermilab. The goal is to complete the charmonium table

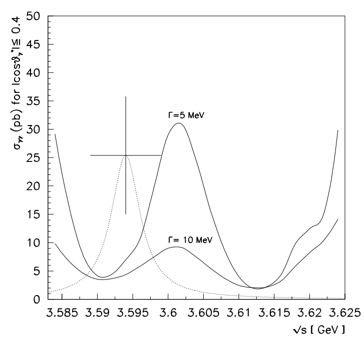

Figure 4: Upper Limit Plot for $\bar{p}p \rightarrow \eta_c' \rightarrow \gamma\gamma$. The solid lines show the 95% confidence level for widths of 5 and 10 MeV. The dotted line shows the rate expected for the η_c' reported by Crystal Ball taking $\Gamma = 5MeV$.

as much as possible and we should clearly like to

- find the η_c' and measure its mass, total width and partial width to $\gamma\gamma$;
- observe and measure the masses of the ${}^{3,1}D_2$ states;
- observe the $\eta_c\gamma$ decay of the ${}^1P_1$;
- measure the width of the ${}^1P_1$;
- improve the measurement of the η_c parameters;
- measure the χ_0 total width and its $\gamma\gamma$ decay.

This program requires an integrated luminosity of 200 pb^{-1} compared to the 30 pb^{-1} we took in E760. To achieve this in a finite running time requires an improved antiproton accumulation rate, and a higher instantaneous luminosity. The antiproton source has achieved accumulation rates in the present collider run a factor of 4 above the rate in E760. To generate higher instantaneous luminosities, the experiment will run with higher initial beam currents and has modified its gas-jet target to provide up to five times its density in E760. A new set of high-rate tracking detectors is being built and a new high-rate data acquisition system has been implemented. As of this writing, the Fermilab fixed-target run will start in mid 1996 and we are looking forward to the challenge of the Charmonium spectrum.

Acknowledgements

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Table 1: Charmonium Resonance Masses and Widths.

Resonance	Mass (MeV/c^2)	Width (keV)
J/ψ (E760)	3096.88 $\pm 0.01 \pm 0.06$	99 $\pm 12 \pm 6$
J/ψ (Old Value)	3096.93 ± 0.09	86 ± 6
χ_1 (E760)	3510.53 $\pm 0.04 \pm 0.12$	880 $\pm 110 \pm 80$
χ_1 (Old Value)	3510.6 ± 0.5	< 1300
χ_2 (E760)	3556.15 $\pm 0.07 \pm 0.12$	1980 $\pm 170 \pm 70$
χ_2 (Old Value)	3556.3 ± 0.4	2600 $^{+1200}_{-900}$
ψ' (E760)	3686.0 (input)	312 $\pm 36 \pm 12$
ψ' (Old Value)	3686.0 ± 0.1	243 ± 43
$^1P_1$ (E760)	3526.2 ± 0.15	≤ 1100

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